Overview of Rayleigh-Taylor Instability and the Impact on Target Design for a Pulsed Fusion / Fission Propulsion System

Brian Taylor
NASA MSFC
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Introduction

• Nuclear propulsion systems have the potential for much higher specific impulse than chemical engines
  – Various concepts have been proposed in the past (NTRs, Orion, etc.)

• If implemented a Fusion based system could way out perform a fission system such as an NTR, but has suffered from technical challenges
  – Confinement at the required density and for the necessary length of time has been difficult to achieve due to plasma instabilities
  – However; a fusion / fission hybrid could relax the confinement requirements
  – Management of the instabilities with mitigating processes could improve confinement

• Interested in the design of a z-pinch target that manages instabilities to achieve fusion / fission reactions for a propulsion system
Rayleigh-Taylor Instability (RTI)

• Most destructive
• Occurs due to acceleration and density gradient vectors in opposite directions
  – Light fluid supports dense fluid
• Small perturbations at interface between fluids quickly grow leading to turbulent mixing
Rayleigh-Taylor Instability (RTI)

• Estimates of growth rates of interest
  – typically calculated with linearized MHD equations
  – Relevant to confinement time

• Interested in cylindrical geometry in which the magnetic field acts as the lighter fluid (density of zero)
  – As in a z-pinch

Schlieren image of z-pinch. Cylindrical geometry disrupted by instabilities

• Image: Ben Dudson, Plasma Instabilities, University of York
What is a Z-pinch?

• A z-pinch a large pulsed current with high $\frac{dl}{dt}$ to generate an azimuthal magnetic field and ionize the target. The current and magnetic field produce the Lorentz force and compress the target.

• This process is one concept for producing fusion reactions.

• The fusion/fission propulsion system concept of interest uses a z-pincho to compress the fuel.
Decades of study and experiment have shown various processes to have mitigating effects upon the growth rate of the Rayleigh-Taylor Instability. E.g. shock waves, tailored density profiles, staged annular collapse, viscosity, shear, and resistivity.

Past experiments should be well understood and used to guide the development of a target for a z-pinch propulsion system.

Several of the following slides highlight particularly interesting experiments.
Wires of Frozen Deuterium used in z-pinch experiments

Unexpected level of stability
- Loss of stability occurred at max current, $dI/dt=0$, and at complete ablation of wire core

Expected contributions to stability
- Sufficient resistivity in plasma
- Ablation of the wire core
• Dielectric coatings have been used to suppress instability development
  – Reduces electrothermal instabilities at the surface which seed RTI
  – Reduced initial perturbations lead to reduced RTI growth

• X-Ray images to the right show large improvement in stability for coated surface
Largest growth rates occur when wave number and magnetic field are perpendicular

An axial magnetic field in the z-pinch of a liner with a pre-ionized gas fill can increase stability

- Magnetic field compresses along with liner

Radiographs show improved stability for higher axial magnetic field in the image to the right
Pulsed Fusion Fission Propulsion System
Concept (PuFF)

- Concept uses a z-pinch to compress the target and burn the fuel through fusion and fission reactions
  - Using a hybrid reaction is intended to relax the conditions under which the plasma must be compressed
- After compression the products are expanded through a magnetic nozzle to produce thrust
- As is the case for other z-pinch applications, RTI is an obstacle
  - Must be managed to achieve successful compression and reaction
  - Stabilizing processes from other experiments may be incorporated into the target design to improve stability and performance
Stability Concepts for Target Design

• **Frozen Deuterium/Uranium Pellet**
  – A cylindrical pellet with a frozen deuterium core and Uranium shell
  • Frozen core and the ablation process may be stabilizing
  – Frozen deuterium or other dielectric outer coating may be used to suppress electrothermal instabilities to further increase stability

• **Uranium liner with Deuterium Plasma fill and Axial B-field**
  – Such a concept may employ the stabilizing effect of an axial magnetic field
  – Dielectric coating may also be used to suppress instability development

• **Staged Collapse of Deuterium/Lithium plasma onto Uranium Pellet**
  – Careful design of the radial density profile, annular stages, and shock waves may stabilize annular plasma shells that could be collapsed onto a uranium pellet
Forward Work

• **Ongoing review of past experiments and analysis**
  – Continued maturation of concepts

• **Modeling of targets and compression using SPFMax**
  – SPFMax is a smooth particle fluid magneto hydrodynamic code under development at the University of Alabama in Huntsville (UAH)
  – Results will influence the design of experiments for Charger 1, a 1 TW pulsed power facility at UAH
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References